Automated rendezvous and capture system development and simulation for NASA

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ABSTRACT

The United States does not have an Automated Rendezvous and Capture/Docking (AR&C) capability and is reliant on manned control for rendezvous and docking of orbiting spacecraft. This reliance on the labor intensive manned interface for control of rendezvous and docking vehicles has a significant impact on the cost of the operation of the International Space Station (ISS) and precludes the use of any U.S. expendable launch capabilities for Space Station resupply. The Marshall Space Flight Center (MSFC) has conducted pioneering research in the development of an automated rendezvous and capture (or docking) (AR&C) system for U.S. space vehicles. This AR&C system was tested extensively using hardware-in-the-loop simulations in the Flight Robotics Laboratory, and a rendezvous sensor, the Video Guidance Sensor was developed and successfully flown on the Space Shuttle on flights STS-87 and STS-95, proving the concept of a video- based sensor. Further developments in sensor technology and vehicle and target configuration have lead to continued improvements and changes in AR&C system development and simulation. A new Advanced Video Guidance Sensor (AVGS) with target will be utilized as the primary navigation sensor on the Demonstration of Autonomous Rendezvous Technologies (DART) flight experiment in 2004. Realtime closed-loop simulations will be performed to validate the improved AR&C systems prior to flight.

Keywords: Automated Rendezvous and Capture, docking, video guidance sensor, AR&C, AR&D

1. INTRODUCTION

The United States does not have an Automated Rendezvous and Capture/Docking (AR&C) capability and is reliant on manned control for rendezvous and docking of orbiting spacecraft. This reliance on the labor intensive manned interface for control of rendezvous and docking vehicles has a significant impact on the cost of the operation of the International Space Station (ISS) and precludes the use of any U.S. expendable launch capabilities for Space Station resupply. The Soviets have the capability to autonomously dock in space, but their system produces a hard docking with excessive velocity (and therefore force) at contact.

Automated Rendezvous and Capture/Docking has been identified as a key enabling technology for the Space Launch Initiative (SLI) Program, Alternate Access to Station, DARPA Orbital Express and other DOD Programs. The development and implementation of an AR&C capability can significantly enhance system flexibility, improve safety, and lower the cost of maintaining, supplying, and operating the International Space Station.

During the 90's, the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) conducted pioneering research in the development of an automated rendezvous and capture/docking system for U.S. space vehicles. Development and demonstration of a rendezvous sensor was identified early in the AR&C Program as the critical enabling technology that allows automated proximity operations and docking. A first generation rendezvous sensor, the Video Guidance Sensor (VGS) was developed and successfully flown on STS 87 and again on STS 95,

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proving the concept of a video-based sensor. Advances in both video and signal processing technologies and the lessons learned from the two successful flight experiments provided a baseline for the development, by the MSFC, of a new generation of video based rendezvous sensor. The Advanced Video Guidance Sensor (AVGS) has greatly increased performance and additional capability for longer-range operation with a new target designed as a direct replacement for existing ISS hemispherical reflectors.

A ground demonstration system for automated guidance, navigation and control (GN&C) and proximity operations (prox ops) software (orbital operations) functional verification was developed. The GN&C, Prox Ops/docking, and collision avoidance maneuver (CAM) software were successfully tested in ground-based simulations that involved both purely digital (computer) simulations and hardware-in-the-loop (HWIL) simulations.

The MSFC also developed "World Class" Agency unique test facilities that allow for the evaluation of rendezvous sensors and automated rendezvous and docking systems. The facilities allow for all-digital software simulations, varying degrees of HWIL simulation, and include orbital lighting simulation.

2. SENSOR DEVELOPMENT

The rendezvous and docking sensors were quickly determined to be crucial to the success of any AR&C system. This led to the development and refinement of a series of video-based sensors. Video was chosen as a simple method of viewing an entire field-of-view at one time while getting fast updates. The VGS (Figure 1) was the first sensor that was developed under the AR&C program for a flight experiment. After the flight experiment, technology advancements, lessons learned, and changing requirements led to the development of the Advanced Video Guidance Sensor.

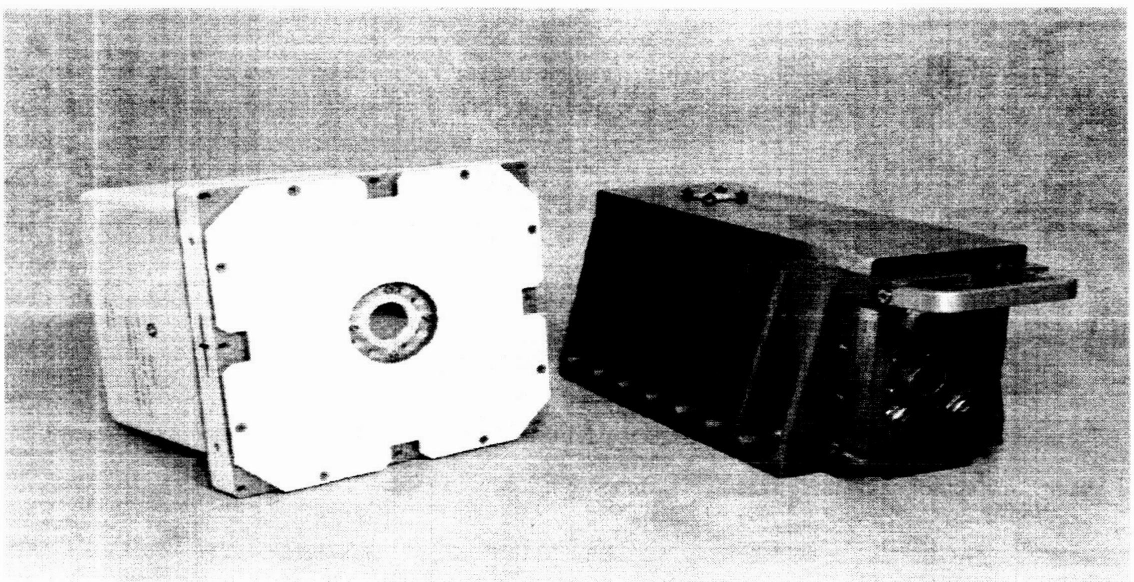

FIGURE 1. Video Guidance Sensor – Sensor Head and Electronics Module.

2.1 Video Guidance Sensor (VGS)

The VGS was designed to provide near-range (from 110 meters in to dock) sensor data as part of an automatic rendezvous and docking system. The sensor determines the relative positions and attitudes between the active sensor and the passive target. The VGS uses laser diodes to illuminate retro-reflectors in the target, a solid-state camera to detect the return from the target, and a frame grabber and digital signal processor to convert the video information into the relative positions and attitudes. The VGS was divided into a sensor head and an electronics module. The sensor head contained all of the optical components (laser diodes, camera, lens, solar rejection filter) as well as heaters and thermo-electric coolers to maintain the temperature of the optical components within their operating range and the electronics module contained the frame grabber, micro-processor, digital signal processor, and control electronics for the sensor head components.

The system was designed to operate with the target within a relative azimuth of ± 9.5 degrees and a relative elevation of ± 7.5 degrees. The system will acquire and track the VGS target within the defined field-of-view between 1 meter and 110 meters range, and the VGS was designed to acquire and track the target at relative attitudes of ± 10 degrees in pitch and yaw and at any roll angle. The sensor outputs the data at 5 Hz, and the target and sensor software and hardware have been designed to permit two independent sensors to operate simultaneously. This allows for redundant sensors using a common target, with each sensor centered on its own short-range target when the chase vehicle and target vehicle are close together.

The on orbit performance of the VGS was exceptional with all the design goals met. The sensor design proved robust with a range of target acquisition and tracking of 150meters + (exceeding the specifications by more than 50%). The sensor was also able to track in all orbital lighting conditions, an important capability to demonstrate for a vision-based system.

Detailed technical papers describing the operation of the sensor and the results of the two flight experiments are available from the referenced Web site at the end of this paper and from (Howard, 1997; 1999a; 1999b).

2.2 Advanced Video Guidance Sensor (AVGS)

The Advanced Video Guidance Sensor (Figure 2) builds upon the successes of the VGS to provide an updated sensor design with increased performance and additional capabilities. The new sensor design incorporates the capability of using an updated target that reduces the area required for target mounting to the equivalent area of the standard ISS

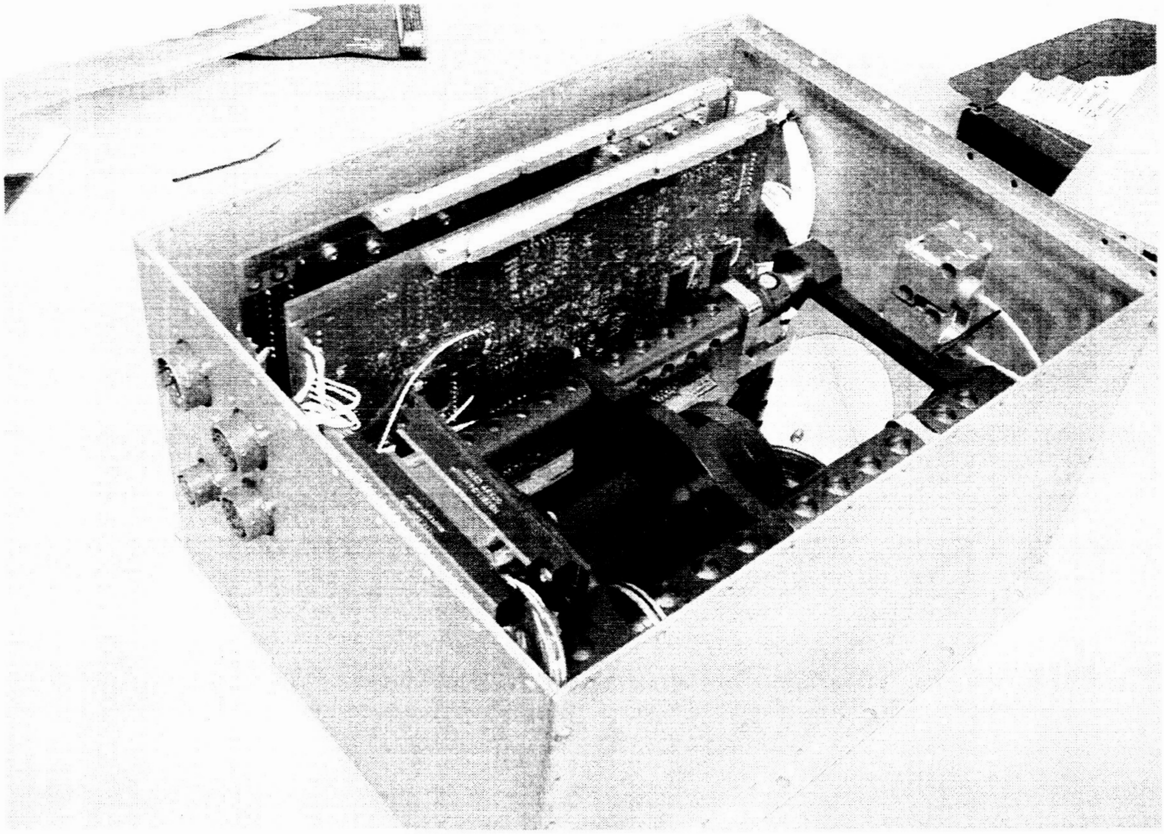

FIGURE 2. The Interior of the Initial Prototype of the Advanced Video Guidance Sensor.

hemispherical reflector assembly. In fact, the new target is a direct replacement for the existing ISS hemispherical reflector and provides all the existing capability plus 6 degree of freedom (6 DOF) information for docking when used with the AVGS. Using a short-range target and a larger-sized target (1 meter long) that has three

1.5-inch (3.8 cm) diameter retro-reflectors, the AVGS will provide relative positions and attitudes from 300 meters down to 0.5 meters. The AVGS operates at data output rates of up to 25 Hz (and tracking rates of up to 75 Hz internally) and can detect retro-reflectors at a range greater that 1 km. The AVGS is a single box design, is low power (<50 W absolute worst case, 15 W nominal), light weight (< 20 lbs) and requires only a 10" by 12" mounting footprint (with a height of 6 inches).

2.3 AVGS Commercialization

The AVGS design is being manufactured by Orbital Sciences Corporation (OSC) under the Demonstration of Autonomous Rendezvous Technology (DART) contract and will become an OSC commercial product. Boeing is planning on purchasing an AVGS from Orbital for the DARPA "Orbital Express" flight experiment as their primary rendezvous and docking sensor.

3. GN&C SOFTWARE DEVELOPMENT FOR AR&C

Engineers at NASA's MSFC have designed and ground tested an AR&C system which, along with the capability to lower mission operation costs, also has a great deal of safety, redundancy and reliability. The MSFC AR&C system incorporates some of the latest innovations in Global Positioning System (GPS) space navigation, video sensor technologies and automated mission planning algorithms as well as the continuous capability for ground and crew monitoring and intervention.

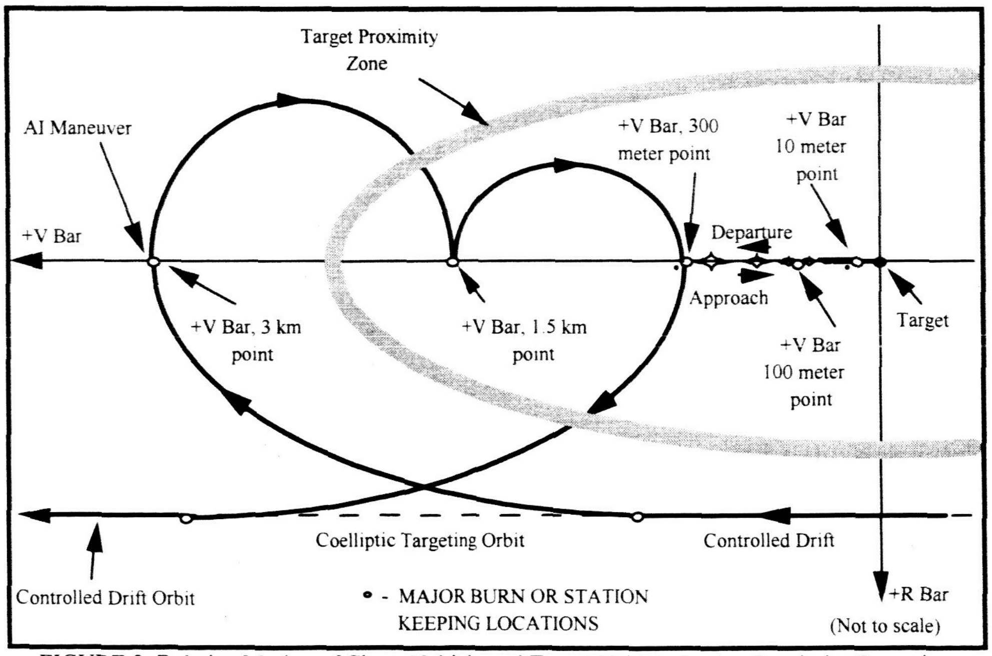

FIGURE 3. Relative Motion of Chase Vehicle and Target Vehicle During Proximity Operations.

The operation of the mission is accomplished by stepping through a set of automated maneuvers, or events, through which the Chase Vehicle (CV) moves in a safe and assured way towards the Target Vehicle (TV) to eventual dock. The modular GN&C software that was developed and ground tested includes the capabilities for onboard mission planning, spacecraft automated orbit transfer and rendezvous, proximity operations, station keeping, capture/docking and collision avoidance maneuvers. The algorithms developed provide the capability to dock with 100 percent success in the absence of multiple system failures.

Event Controller is the function that keeps track of the current mission event, when to switch events and even when to change entire event sequences. Each event has a set of predefined parameters that allow the GN&C system to perform certain tasks or maneuvers. These parameters include guidance targets, expected transfer times, approach corridor limits and approach speed limits. When the Event Controller determines that an event has been completed successfully, it transitions to the next event. One event type, rendezvous, automatically performs numerous orbital transfers and plane changes to take the CV from the orbit insertion point to the proximity zone of the TV. All other event types are executed within the proximity zone (Figure 3) and include controlled drift, Clohessy-Wiltshire (CW) transfer, station keeping, forced approach and finally terminal autopilot.

If the Event Controller determines that an event has not been successfully completed, a CAM is activated and the Collision Avoidance Maneuver Executive function is given control of event execution. After the CAM is completed, the Event Controller decides which event to restart with, or if need be, the ground can upload an entire new mission sequence. The AR&C system also allows for an update of these events during a nominal mission.

The software algorithms developed under the MSFC AR&C Program have been transferred to Orbital Sciences Corporation for implementation as the flight control software to be demonstrated, on orbit, during the DART flight experiment.

Two technical papers with detailed descriptions of the development of the AR&C system and its performance in the ground test environment are available from the Web site referenced at the end of this paper and are available in (Cruzen, 1999; 2000).

4. AR&C SYSTEM GROUND TEST PROGRAM

Following the development of the VGS rendezvous sensor and the development of the AR&C System modular GN&C software, MSFC conducted extensive testing of the AR&C System in a high fidelity ground test environment with two GPS receivers, a flight computer emulator running the MSFC developed GN&C software and a rendezvous sensor or model (depending on range) in the simulated vehicle control loop.

The decision to use a model or hardware for the rendezvous sensor is a function of the internal dimensions of the test facility. The VGS model used for long-range rendezvous used flight data for performance verification. Once a 40-meter standoff was achieved, VGS hardware was substituted for the model and docking was achieved using actual rendezvous sensor hardware in the simulated vehicle control loop.

The performance of the MSFC AR&C System was exceptional during this approximately 6 months test and demonstration series. The developed system proved to be very robust. The detailed test results from the ground test and demonstration program are presented as a conference paper that is available from the Web site referenced at the end of this paper (Cruzen, 2000).

4.1 Agency Unique Test and Evaluation Facilities

The Flight Robotics Laboratory (FRL) at MSFC was developed with the objective of providing simulation and hardware-in-the-loop test support for the design, development, integration, validation and operation of space vehicle systems. The use of simulations (the duplication of known or expected mission variables into a training or research program) has proven to be a low cost, low risk means of investigating overall system performance. The FRL has been reviewed by the National Facilities Study, commissioned by Vice President Gore, and is considered to be a world class facility, unique among engineering test facilities.

The facility is centered around a 44 foot by 86 foot precision air bearing floor, the largest of its kind. A mobility base called the Air Bearing Spacecraft Simulator (ABSS) is used on the air-bearing floor and will hold up to a 400-pound payload. A service area is located adjacent to the flat floor and is used for replenishing of pneumatic and electrical systems on the ABSS. An 8 degrees-of-freedom (DOF) overhead gantry, called the Dynamic Overhead Target Simulator (DOTS) provides a 1000-pound payload capability for simulating relative motion with respect to a fixed target on the facility floor. A computer system provides inverse kinematics and allows the gantry to act as a target or as the 6 DOF rendezvous vehicle. The target reaction dynamics are simulated through force/torque feedback from sensors mounted at the payload interface. The Facility also contains an orbital lighting simulator that provides critical capability to evaluate any vision based sensor concept. The FRL has been utilized by the MSFC AR&C Program for the successful development of the MSFC AR&C System, development and testing of the Advance VGS for DART and in support of the DARPA "Orbital Express" Program. The DART rendezvous GN&C system will also be tested in the Facility.

The FRL provides the ideal environment for the test and evaluation of rendezvous subsystems and systems in a simulation environment validated by on orbit data. See the referenced Web site for details of the FRL.

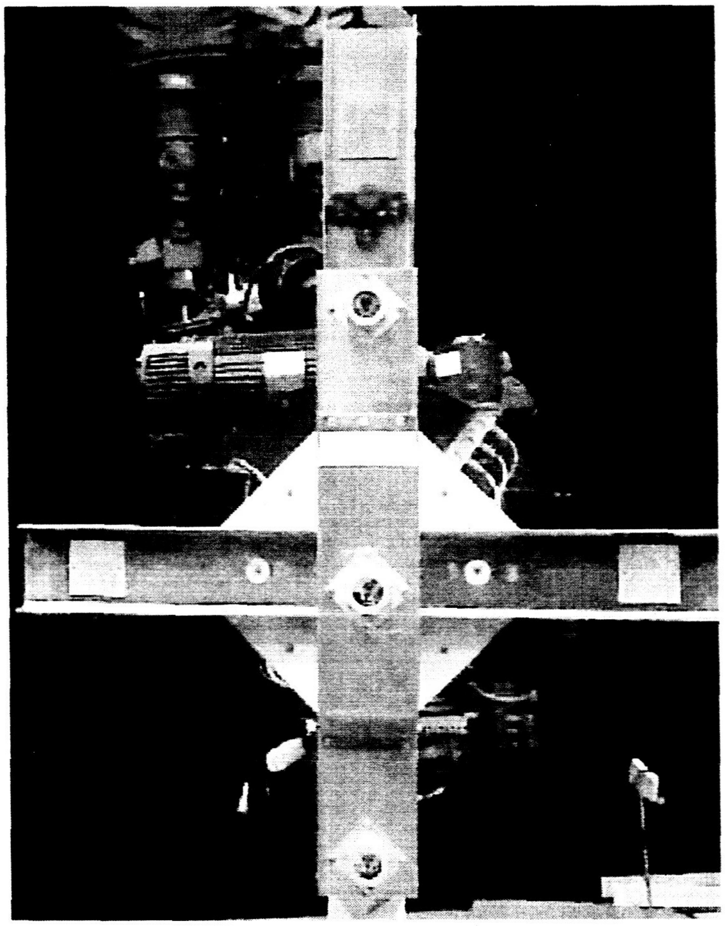

Figure 4. MUBLCOM target mockup mounted on the DOTS

4.2 Hardware-in-the-loop (HWIL) testing for DART

The DART mission will center around the Advanced Video Guidance Sensor (AVGS) providing range and 6 Degree of Freedom (6 DOF) information based on recognizing and tracking a cooperative target mounted on a communications satellite. A real-time closed-loop simulation to exercise the AVGS in a dynamic environment is the last in a series of navigation system tests prior to the launch of the DART vehicle. Four test trajectories have been selected to demonstrate critical portions of the proximity operations portion of the mission. Modified to fit within the facility constraints of the

Flight Robotics Laboratory, the simulations will functionally demonstrate: 1) the approach of the DART vehicle towards the satellite along the V-Bar, transfer to the docking axis and approach to 5 meters; 2) the nominal approach with prescribed satellite dynamics; 3) a nominal approach with a Collision Avoidance Maneuver (CAM) exercised on loss of sensor data; and 4) an approach with a vehicle scan maneuver designed to locate the target relying on secondary navigation sensors.

For this testing, the target will be mounted on the DOTS (see Figure 4) and the sensor will be mounted on a stand at one end of the FRL. The spacecraft approach will be measured with the AVGS as well as resolvers and encoders on the DOTS, so there will be two independent measurements of approach trajectories during the HWIL tests.

4.3 Recommendations for continuing development of AR&C for use with the ISS

The MSFC AR&C Program has developed and successful demonstrated two critical elements in the development of an operational capability for automated rendezvous. These elements are: 1. The development and on orbit demonstration of the rendezvous sensor; and 2. The successful development and demonstration of the robust, modular, GN&C software required for automated orbit transfer, rendezvous, proximity operations and docking and the capability for a collision avoidance maneuver in the event of an equipment failure or other anomaly.

Some of the work required to complete the development of an operational AR&C capability for use with ISS includes the development of ISS accommodations for AR&C (a vital task involving much communication between the ISS operations personnel and AR&C development personnel. These accommodations would include such things as docking mechanisms and/or docking locations for an automated vehicle to use, targets mounted on the ISS near the docking locations, methods of communication between the ISS and the AR&C system on the visiting vehicle, and the development of flight operations and flight rules for AR&C operations with the ISS. Both the flight rules and flight operations would have to be verified and validated through flight demonstrations (which could use Shuttle flights to the ISS for test purposes.) Also, the entire AR&C system would have to be validated through flight experiments and demonstrations, starting with demonstrations using Shuttle flights to the ISS.

5. AR&C SYSTEM DEMONSTRATION IN SPACE

The DART flight experiment is planned for April 2004. DART will be the first "in space" demonstration of an AR&C System capability for the NASA. The experiment is to be launched on an Orbital Sciences "Pegasus" launch vehicle. The rendezvous spacecraft will perform orbit transfer, rendezvous, and proximity operations (station keep within 5 meters) with a DARPA MUBLCOM satellite that is already in orbit. The demonstration will validate the modular MSFC GN&C algorithms that have been adapted, by Orbital, to the rendezvous spacecraft. DART will also validate the operation of the AVGS in the orbital environment and demonstrate both station keeping and a fly around capability. The demonstration will last approx 48 hours before the chaser spacecraft deorbits to a safe non-collision orbit and eventually re-enters the atmosphere.

6. CONCLUSIONS

The MSFC AR&C program has been extremely successful. It has accomplished two successful flight experiments of the Video Guidance Sensor on STS-87 and STS-95. The work on the VGS, AVGS, and AR&C has led to a number of patents, publications, and conference presentations. The entire AR&C system has been tested extensively in both software and hardware-in-the-loop simulations in ground tests in the Flight Robotics Laboratory at MSFC. System and component improvements will continue to be tested. The Advanced Video Guidance Sensor, with marked performance increases over the VGS, is being developed for a flight in October, 2004 and is being presented as a commercial product by Orbital Sciences Corporation. The DART mission will be flight-validating the rendezvous and proximity operations GN&C software as well as the AVGS sensor performance. The AR&C system is ready for use!

ACRONYMS AND ABBREVIATIONS

AR&C/D/M	Automatic Rendezvous & Capture/Docking/Mating
AVGS	Advanced Video Guidance System
CAM	Collision Avoidance Maneuver
CV	Chase Vehicle
DARPA	Defense Advance Research Projects Agency
DART	Demonstration Automatic Rendezvous Technology
DOD	Department of Defense
DOF	Degrees of Freedom
DOTS	Dynamic Overhead Target Simulator
FRL	Flight Robotics Laboratory
GN&C	Guidance Navigation and Control
GPS	Global Positioning Satellite
Hz	Hertz
HWIL	Hardware-in-the-Loop
ISS	International Space Station
Km	Kilometer
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
SLI	Space Launch Initiative
STS	Space Transportation System
TV	Target Vehicle
U.S.	United States
VGS	Video Guidance Sensor

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Note: All technical material, conference presentations, etc. mentioned in this paper, and additional information on the MSFC AR&C Program is available through the following web site: **http://alternate.msfc.nasa.gov/AR&C**

Should you encounter problems, Netscape 6.2 is recommended for viewing the contents of the site.

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